DESIGN AND WIND TUNNEL TESTING OF GUIDANCE PINS FOR SUPERSONIC PROJECTILES

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ABSTRACT

In this paper, the results of a series of experiments funded by DARPA to determine the feasibility of using small actuators to provide directional control for a supersonic projectile are presented. Controlling the flight of the projectile was accomplished by taking advantage of complex shock-boundary layer interactions produced by mechanical devices. One set of wind tunnel tests performed at the Georgia Tech Research Institute characterized the force levels produced by the small actuators on a scale model, while another set of experiments determined the optimum geometry and location of the actuators. The end result of the experiments was to demonstrate that the use of pin based actuators for guidance is a feasible method to control the flight of supersonic munitions.

1. INTRODUCTION

There has been a recent interest in both missiles and guided projectiles that operate in the high supersonic to hypersonic range for various missions. ONR has been pursuing HyFly since early 2002 (Kandebo, 2002). HyFly is a proposed Mach 6 missile that would be used to strike targets of opportunity in a timely fashion before they could reposition. Other areas of interest include cruise missile defense such as DARPA's Low Cost Cruise Missile Defense (LCCMD) program and the Army's Maneuver Air Defense System (MADS). One possible scheme for missile defense assumes that large caliber guns (2 inch or larger) with high rates of fire could fire multiple supersonic projectiles that could be guided into an incoming missile that may be undergoing evasive action as shown conceptually in Figure 1. Warnash and Killen, 2002, describe several military programs where high speed guided munitions are in development or are under consideration. In all cases, it is found that the high closure rates between the projectile and the target may necessitate large turning forces.

It was the goal of this effort to provide an initial feasibility study into the use of strategically located actuators to provide the turning force needed to terminally steer a missile or projectile. Initially only jet actuators were considered. These jets were not intended to be simple reaction jets, but were intended to modify the flow around the projectile in such a way as to greatly enhance the force on the body of the projectile. As the research progressed, the use of deployable pins was also evaluated to generate turning forces. Efforts were made to understand the physics behind these turning forces so that the lessons learned here could be applied to future missile and projectile geometries.

The work presented here describes only the most recent efforts of a 3 year program. Earlier work using jet actuators and earlier work using cruder experimental apparatus is not described due to space limitations and remains unpublished at present.

2. GUIDANCE PIN CONCEPT

Research using active flow control on subsonic munitions for the purpose of steering led to further efforts on supersonic munitions. The early research on supersonic fin-stabilized projectiles showed that the same actuators that worked on subsonic rounds were not applicable to supersonic rounds and that actuators that took advantage of the supersonic flow via shock interactions were likely candidates. Thus the early research led to patent pending*, pin-based actuators for guidance shown conceptually in Figure 2. Here two pins are shown deployed near the tail of supersonic round and the complex 3-D shock interaction between the pins, body and fins is also shown. This shock generates asymmetric forces on the body that can produce both rolling and pitching moments to provide steering capability. It is the research into the appropriate placement and geometry of these pins as well as the mechanisms to insert and retract into the flow that is described in this paper.

Multiple pins would be needed for full control of a projectile and 6-DOF studies have shown that three pins is probably the optimum number of pins, though 2 and 4 pin configurations are also viable. Figure 3 shows two

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* The use of these actuators or similar actuators to produce steering forces and moments is a proprietary technology developed by the Georgia Tech Research Institute and is protected under US Patent Law. Patent Pending.

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14. ABSTRACT

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separate pin configurations that produce a rolling moment, left, and a pitching moment, right. An example of the resulting pressures generated by the shock interactions is provided in Figure 4 where surface pressure contours from a CFD run are shown. Here it is clearly seen that both high pressures are generated on the fin and on the projectile body. For the roll control configuration shown on the left in Figure 3, the body forces on opposite sides of the projectile cancel and the forces on the fins result in a pure rolling moment. For the directional control configuration shown on the right in Figure 3, the body forces and the fin forces combine to produce a strong pitching (or yawing) moment that serves to induce an angle of attack on the projectile. The projectile will thus fly at an angle of attack that generates a large side force and a high g turn.

Work continues on developing the concept, but roll moment generation has been demonstrated on an actual fired round at the Army Research Lab as reported by Silton, 2004. A 25 mm projectile was fired at ARL that demonstrated that the projectile could be rolled some 170° in 13 ms after deployment of the pins. Shadowgraphs such as that shown in Figure 5 from the ARL tests also allowed for further validation of the experimental, CFD, and 6-DOF results generated previously. These tests proved that the experimental tests in the laboratory could be applied on actual fired rounds. In the next set of tests at ARL which should occur early 2005, a projectile will be made to divert after being fired from a gun.

3. ½ MODEL EXPERIMENTS

To experimentally measure the forces and moments produced by a pin on a projectile, a full scale wind tunnel model was machined. The test article, shown from three views in Figure 6, was essentially a projectile split along a longitudinal plane that was based on a geometry for which some analysis had been previously conducted by Whyte et al., 2002. As shown, the underside of the projectile was hollowed out to allow for a tungsten slug near the nose to move the cg forward and hollowed out near the tail to allow for pin actuators to be installed. In Figure 6, a hole can also be seen near the center of the model. A shaft was threaded into this hole to connect the model to the force and moment balance. Before testing, the model was trimmed with weights such that its cg was along the mounting shaft which corresponded to nominal cg of a stable penetrator round. The model projectile was immersed in a Mach 2.5 stream with a ground plane isolating the underside of the projectile as shown in Figure 7 where the Mach 2.5 convergent divergent nozzle is seen on the right. Flow visualization was used to determine that the shock generated by the sharp leading edge was weak and only resulted in decreasing the flow Mach number to 2.469 from 2.475 and turning the flow 0.3° into the model.

Force and moment measurements were made using a series of strain gage type force sensors. As noted previously the model was supported by a steel shaft that passed through the ground plane. This shaft was constrained by two sets of rotary bearings which allowed the model to rotate freely, however the shaft was constrained from rotating by a moment arm. This arm was coupled to a force sensor that measured the force at the end of the moment arm and thus the moment on the projectile. The moment measuring apparatus was attached to a frame that was supported by an air bearing that provided nearly frictionless side to side movement of the projectile and moment apparatus. This side to side motion was constrained by two load cells which provided a measurement of the lateral force on the projectile. All of the force apparatus can be seen along with the signal conditioners in Figure 8.

Initial measurements involved a simple pin actuator where the height of the pin was varied by hand using a micro positioner. An aft photograph of the model with this positioner and the pin fully extended is shown in Figure 9. This setup allowed for the pin height to be varied and for a rapid determination of the variation in the forces and moments with pin height. With this set up the pin height could be varied from flush with the body to a mean height of 3.3 mm. Thus at max height there was a one to one ratio of the pin width (cross stream dimension) to pin height. For these experiments, the pin used had a trapezoidal shape as earlier experiments provided some indication that this geometry provided the maximum force of those geometries tested.

The side forces developed by the projectile at various angles of attack at Mach 2.47 were measured both with the pin flush and at 4 pin heights. The measured forces are plotted in Figure 10 where it can be seen that the aerodynamic forces on the body clearly dominate the forces developed by the pin. One can more clearly see the effects of the pin when one examines the moment data shown in Figure 11 where much more pronounced differences are seen. In Figure 11, it can be seen that the moments generated are not linear with pin height and that for a pin height of 1 mm the change in the moments is barely observable. This was explained via optical measurements that showed that the boundary layer on the projectile was on the order of 1.8 mm. Thus it was concluded that the pin must protrude through the boundary layer to have a significant effect. Further, one can note that for a pin height of 3.3 mm, the aerodynamic moment on the body and the moment generated by the pin nearly cancel at an angle of -5° indicating that the projectile should fly at an angle of 5° relative to the flow with the pin deployed. By decoupling the moment arm from the shaft, the projectile was free to rotate and this observation was verified. Thus by inserting the pin into the flow, the projectile was forced to fly at an angle of attack which produced nearly 7 lb of force (see Figure 10) on a half body. These experiments when coupled with CFD that was run in parallel provided strong indications that these pin based actuators would provide a viable means of steering supersonic projectiles.

Further work remained however with regard to determining the time required for these forces to develop and in devising a mechanism that would not only actuate the pin on command, but do so in a fashion that would fit inside the body of the projectile. Initial efforts at mechanizing the pin used the same pin mounting scheme shown in Figure 9 with the linear slide replaced by a solenoid. This mechanism was able to rapidly deploy the pin, but once the pin was deployed the aerodynamic drag on the pin introduced enough torque that the solenoid was unable to retract the pin. Another mechanism was developed that used a stepper motor in combination with a rack and pinion type arrangement. This mechanism was able to deploy and retract the pin and had the advantage of providing position feedback via the encoder; however, this system had two major drawbacks. First, it took around 75 ms for the pin to deploy, which corresponds to something around 100 m of travel for a Mach 4 projectile, and this was felt to be too slow. Second, this arrangement was too large to be packaged inside the projectile. Nevertheless, these preliminary experiments were successful in the sense that it was determined that there was no measurable time lag between the force generated and the pin deployment.

From the lessons learned from these first attempts at actuating the pin motion, a new pin deployment concept was developed that tried to take advantage of the aerodynamic forces on the pin. Instead of linearly driving a pin in a motion normal to the projectile body, a pin was developed that pivoted into to the flow. This 'rocker pin' could be configured such that the aerodynamic forces held the pin in the up position or in the down position which means that the actuator only has to provide force in a single direction. This opened other actuation techniques such as those based on pressure. A solid model representation of such a setup is shown in Figure 12 where the rocker pin is red and is oriented such that the flow would tend to force the pin to be flush with the projectile body. For the rocker pins, all of the drag force is carried by the shaft about which the pin rotates and thus an actuator need only supply a moment. One may also note from Figure 12 that the portion of the rocker pin inside the projectile body is longer than that in the flow. This setup provides a mechanical advantage such that less actuator force is required to hold the pin into flow. Both factors serve to reduce the actuator force required, and thus the next tests used this rocker pin concept. A photograph of a rocker pin installed on the wind tunnel model is shown in Figure 13 where it can be seen that the pin shape roughly follows the contour of the body.

In the laboratory, a pneumatic cylinder was used to rotate the rocker pin into the flow and pin position feedback was provided by a cable device. The cylinder was driven by shop air and a mini valve was used to meter air to the cylinder. Using this hardware, it would be possible to house up to 4 pneumatic cylinders and a gas cartridge into the projectile body, though the valve hardware remains to large. Measurements were made of the pin deployment time and the accompanying force rise using this setup. In Figure 14, a 2 second time capture is shown where traces of the force and moment on the projectile are shown along with the signal to the valve and the pin position feedback. It is seen that the force and moment very nearly track the pin position. By zooming in on the pin deployment event, Figure 15, further evidence is provided that there is little time lag in the force and moment. Further it can be seen that the pin deploys very rapidly through the initial range of motion and then more slowly through the last portion of insertion. It turns out that this is quite desirable as it avoids projectile AOA overshoot and oscillations in AOA as discovered in 6-DOF analysis. (The oscillations in the present data are found without pin deployment and are an artifact of the experimental apparatus.) These experiments demonstrated that the rocker pin could be rapidly deployed and that the force and moment rise times could be considered instantaneous for the purpose of developing control algorithms. (What is measurement dt?)

4. PIN-FIN PARAMETRIC STUDIES

While advancing the technology needed to eventually actuate the guidance pins, it was realized that the many constraints on any future design might necessitate changes in the pin geometry and or location. For example, it was originally desired to use complex pin geometry on the rounds in the range tests at ARL, but cost constraints led to the choice of a round pin. Also, for the rocker pin design, the pin more closely resembled a flat pin than either a round or trapezoid pin since its frontal surface needed to correspond to the projectile body. Thus further investigation was warranted into determining the effects of pin location and pin geometry on the forces and moments developed.

By combining the force balance from the ½ projectile experiments and hardware previously used to determine the optimum pin location in combination with precision machined pins, a series of tests were conducted that parametrically varied the pin location and the pin geometry. A picture of the experimental setup is shown in Figure 16 where a pin can be seen next to a fin. For these tests, a Mach 1.7 round nozzle was used as the Mach 2.5 nozzle was not large enough to fully immerse the test fin. A close up of the round pin and the fin is shown in Figure 17 where the interchangeable blocks on the ground plane that allowed different pin positions may also be seen. Four different pin geometries were tested and these pins are shown in Figure 18. The streamwise dimension of the pins was 0.2 in for all of the pins with the exception of the Round 0.1 pin, which has a diameter of 0.1 in. As seen on the far right of Figure 18, the trapezoidal pin experienced structural failure during testing thus limited data is available for this geometry, yet the failure also pointed to a weakness in this geometry.

The side force on both the fin and the pin were measured for 90 different locations in a 9 x 10 matrix that was 0.55 inch in the spanwise direction and 0.88 inch in the streamwise direction. The grid originated at 0.1 inch from the surface of the fin which means the larger pins were flush with the fin as the pin position was defined by its centroid. The most aft streamwise location was 0.185 inch upstream from the fin trailing edge. The forces measured at each location were used to generate the force contours shown in

Figure 19 which shows that while there is a clear optimum location there is a region where the pins could be located without a severe drop off in the force produced. Interestingly the force contours have nearly identical shapes for both the round and the rectangular pins though it is clear the rectangular pin generates more force.

The similarity in the contours between the round and rectangular pins seemed to indicate that there was some universal optimum location that maximized the force. It was found that the Round 0.1 pin also had a similar force contour and thus attempts to collapse the optimum distance from the fin on a nondimensional basis such as the distance over the pin diameter failed. The best collapse found is shown in Figure 20 where the optimum distance from the centroid of the pin to the fin appears to be independent of pin size or geometry. Obviously, the sample size under investigation is too small to support this conclusion which can not hold for all pins. The normalization of the force was more successful as the force scaled with the frontal area of the pin. As seen in Figure 20, with this scaling the two round pins nearly collapse on each other and the rectangular pin develops more force. When the rectangular, round, and trapezoidal pins are compared directly, Figure 21, it is clear that the flat pin induces the most side force. This is readily explained as the rectangular pin should introduce the most flow disturbance as there will be three dimensional relieving effects on the round and the trapezoidal pins resulting in a weaker shock structure and less induced force.

5. CONCLUSIONS

These experiments have demonstrated the viability of using pin based actuators for guidance of supersonic fin stabilized rounds. It has been shown that the location of the pins is critical to generating the required forces though some leeway exists. The geometry of the pin also affects the force generated, and it was shown that rectangular pins generate more force than round pins. Work remains on generating actuators that can be packaged into a projectile though advances were made during the research and a rocker pin concept has been developed that reduces the forces required to actuate the pins. It was also demonstrated that the pins could be made to actuate in a very short time and that there is no measurable lag in the rise of the aerodynamic forces. To achieve a 50 g turn on the projectile under consideration, a mere 10.5 N of force is required to develop the 400 N of turning force required as detailed in which is nearly a 40:1 gain.

6. ACKNOWLEDGEMENTS

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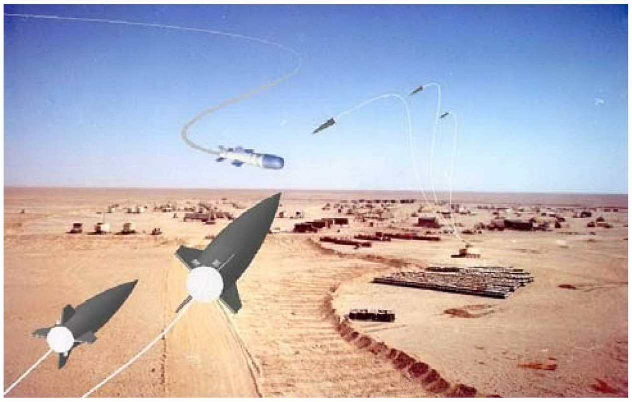


Figure 1 Guided munition defense of a forward base against cruise missile attack.

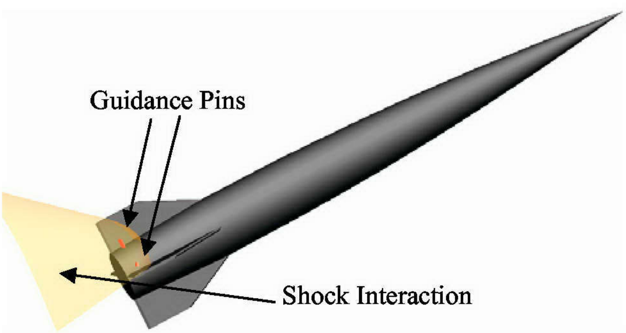


Figure 2 Pin-fin guidance concept (patent pending).

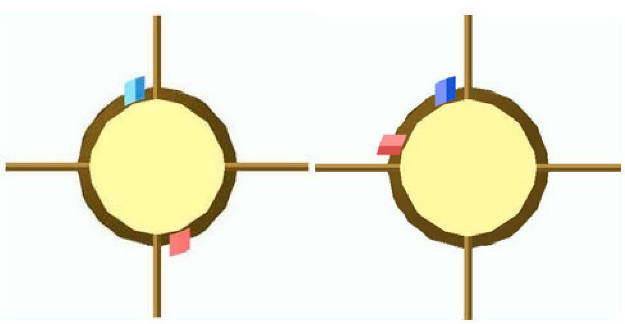


Figure 3 Pins used for roll and directional control.

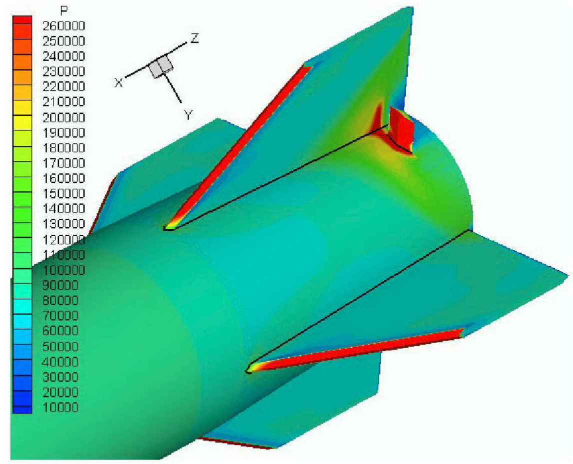


Figure 4 Surface pressures for pin with projectile at zero angle of attack, roll control configuration.

Figure 5 Shadowgraph of fired projectile at ARL with roll control pins. (CAD image superimposed.)

Figure 6 Wind tunnel model of projectile.

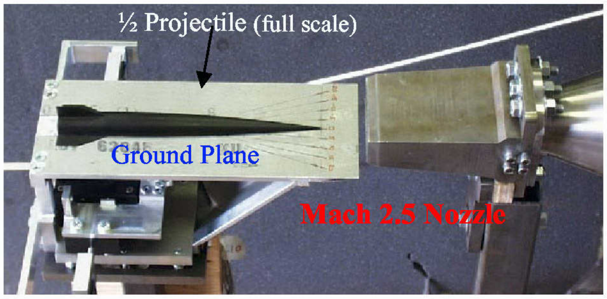


Figure 7 Top view of half model setup.

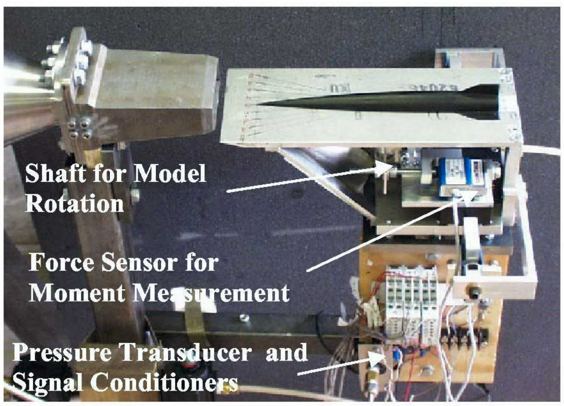


Figure 8 Instrumentation view of half model.

Figure 9 Manually positioned actuator hardware.

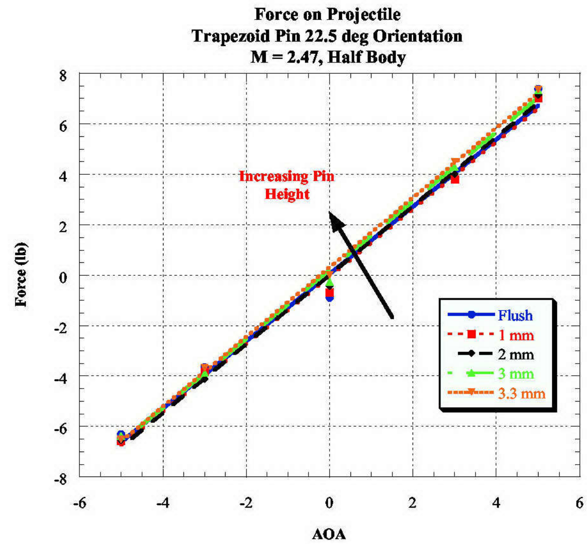


Figure 10 Experimentally measured forces on half projectile for various pin heights.

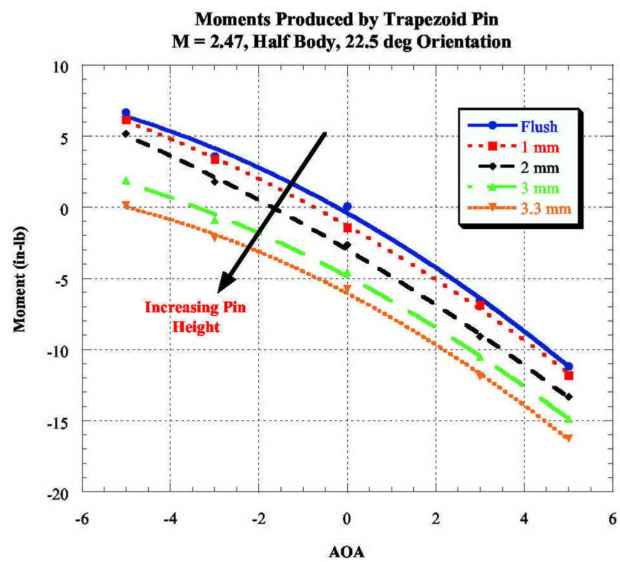


Figure 11 Experimentally measured moments on half projectile for various pin heights.

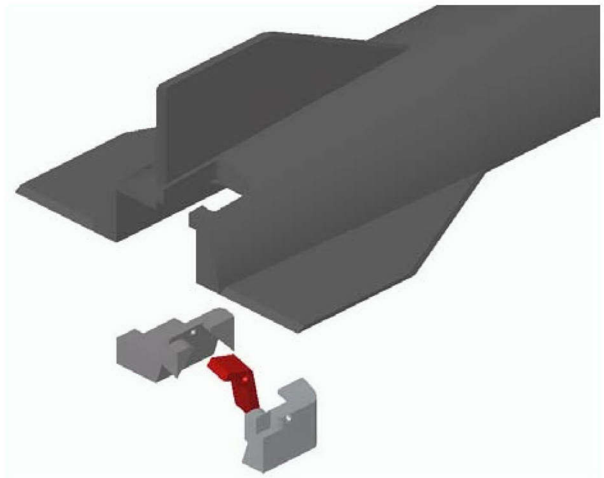


Figure 12 Rocker pin exploded assembly.

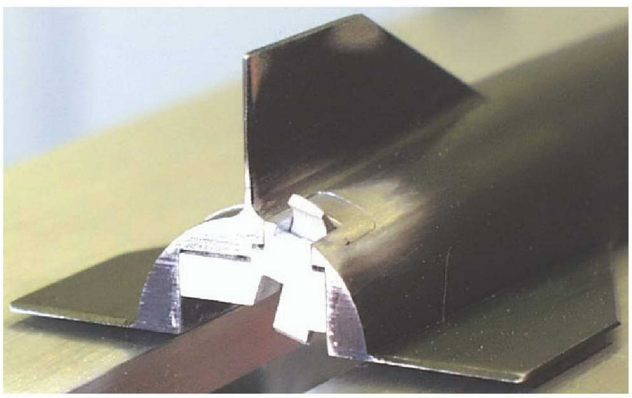


Figure 13 Rocker pin installed on wind tunnel model.

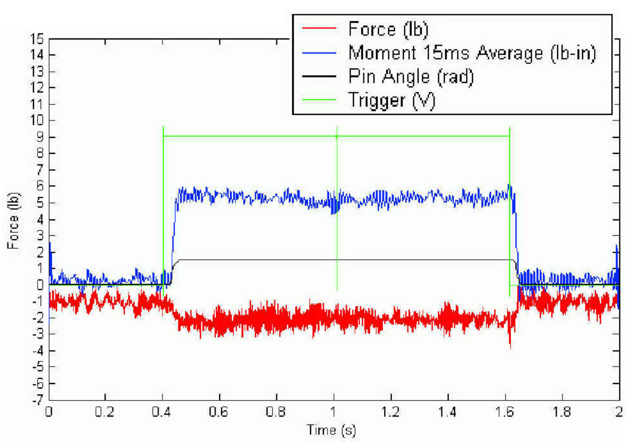


Figure 14 Time history of forces and moments for pin insertion. ($\Delta t = 30.5\ \mu s$)

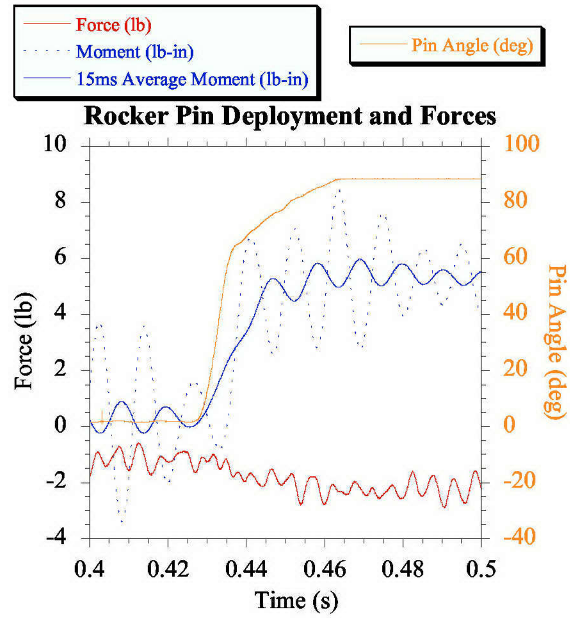


Figure 15 Time history of forces and moments for stepper motor pin insertion.

Figure 16 Experimental setup for pin-fin parametric studies.

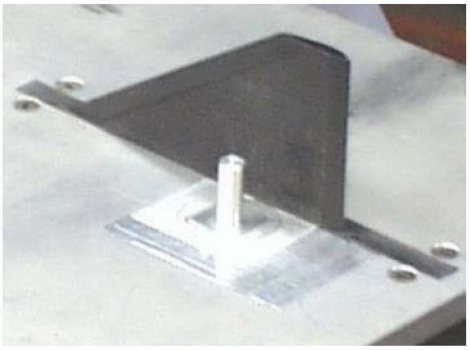


Figure 17 Close up of round pin and fin.

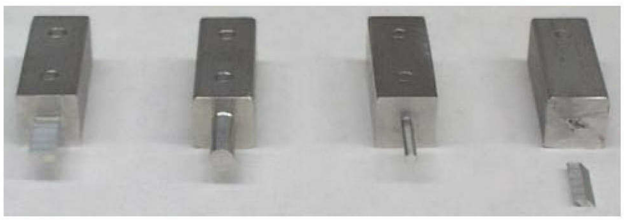
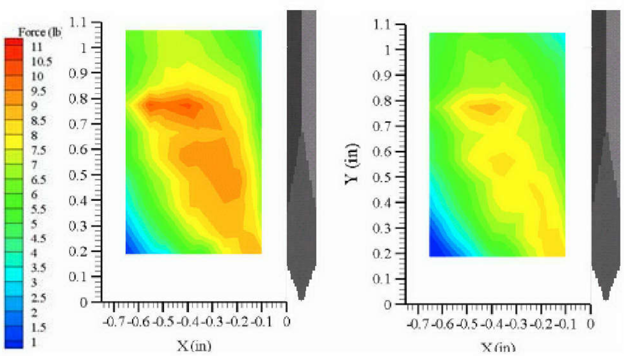


Figure 18 Pins used in experiments. (From left to right, Rectangle, Round 0.2, Round 0.1, and Trapezoid Pins.)



Rectangle Round 0.2

Figure 19 Force contours as a function of pin location.

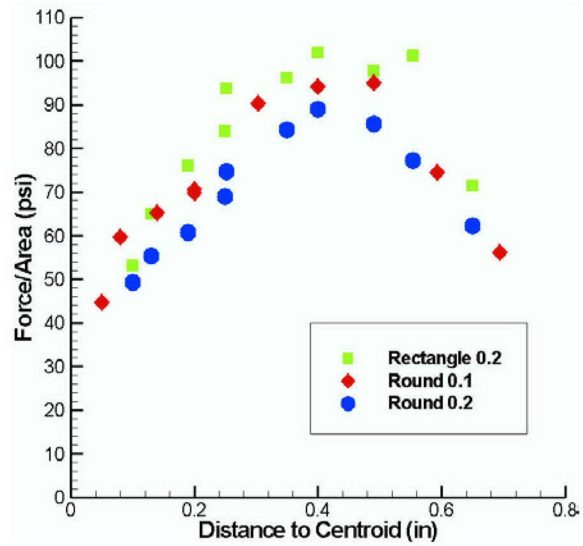


Figure 20 Force normalization for various pin geometries.

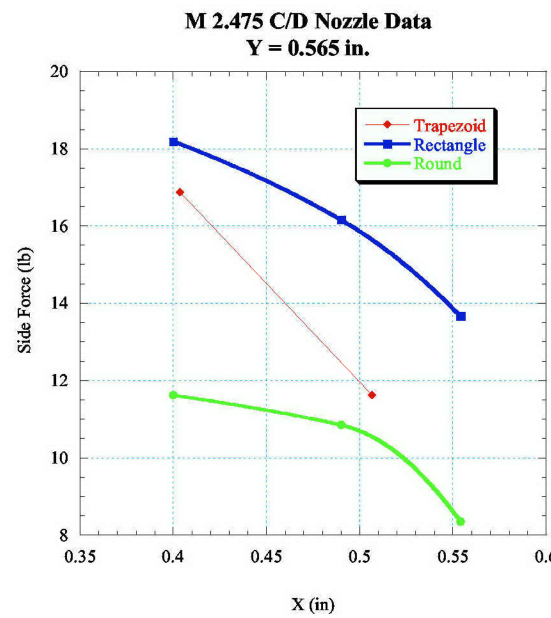


Figure 21 Effect of pin geometry on induced force.

Force to Deploy 2 Pins	10.5 N
Pin Induced Force	30 N
Moment Arm	0.11 m
Steering Moment	3.3 N-m

Projectile Mass	0.816 kg
For a 50g Turn	400 N
AOA Required	7.1°
Static Margin	8 mm

10.5 N Input ⇨ 400 N Guidance

Figure 22 Force gain of pin actuators.